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A Review of the Status and Needs for the Quantitative Prediction of Convective Precipitation

by

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A REVIEW OF THE STATUS AND NEEDS FOR THE QUANTITATIVE PREDICTION OF CONVECTIVE PRECIPITATION

Final Report Prepared for

Hydrometeorological Research Division
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by

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ABSTRACT

Current operational numerical weather prediction models handle quantitative precipitation forecasting on the synoptic scale reasonably well. However, mesoscale convective precipitation events are much more difficult to predict. The smaller spatial scales, the inability to define initial conditions with adequate spatial resolution, and the more rapid development and evolution of these systems appear to be the main reasons that the large-scale atmospheric models fail. Mesoscale convective precipitation events, such as heavy rainfall, flash floods, wind storms, ice storms and blizzards, have the most substantial economic impact and consequently are most important for operational weather forecasting.

The key to improving forecasts and warnings of mesoscale weather is a better understanding of the physical and dynamical processes governing these phenomena.

Four approaches have been identified to provide short-term forecasts of mesoscale weather events. The first approach extrapolates detailed observed weather patterns, the nowcasting approach. The second approach uses Model Output Statistics and statistical methods. The third approach uses pattern recognition techniques, or the subjective method used by forecasters. The fourth approach, the dynamical method, involves the prediction of mesoscale events using numerical models.

The products generated by the nowcasting approach can be expected to be better for forecast periods of 0-4 hours because they more effectively represent the fine-scale variability. For longer periods, development and decay become more important and the products of the numerical models become better. It is not a question of one method being better than the other, rather they should be viewed as complementary with each being appropriate for a particular time and space scale.

Résumé

Les actuels modèles numériques de prévision météorologique traitent raisonnablement bien la prévision quantitative des précipitations à l'échelle synoptique. Cependant les épisodes de précipitations de convection à moyenne échelle sont beaucoup plus difficiles à prédire. Les échelle spatiales plus petites, l'inaptitude à définir des conditions initiales avec une résolution spatiale convenable et la formation ainsi que l'évolution plus rapides de ces systèmes semblent constituer les principales raisons pour lesquelles les modèles à grande échelle de l'atmosphère ne fournissent pas de bonnes prévisions. Les épisodes de précipitations de convection à moyenne échelle comme les fortes chutes de pluie, les crues soudaines, les tempêtes de vent, les tempêtes de verglas et las blizzards ont une incidence économique des plus importantes et sont par conséquent importants en prévision météorologique opérationnelle.

Le facteur fondamental de l'amélioration des prévisions et des avertissements concernant ces conditions météorologiques à moyenne échelle est une meilleure compréhension des processus physiques et dynamiques régissant cas phénomènes.

Pour la prestation de prévisions à court terms sur les épisodes météorologiques à moyenne échelle, quatre approches ont été identifiées. La première, qui fait intervenir l'extrapolation des configurations météorologiques détaillées qui sont observées, est dite de visualisation du temps. La deuxième exploite les statistiques des sorties des modèles et les méthodes statistiques. La troisième approche est basée sur des méthodes de reconnaissance de configurations, c'est la méthode subjective utilisée par les prévisionnistes. La quatrième enfin est la méthode dynamique qui aborde la prévision des épisodes à moyenne échelle au moyen de modèles numériques.

On peut s'attendre à ce que les produits obtenus par l'approche de visualisation du temps donnent de meilleurs résultats pour des intervalles de prévision de 0 à 4 heures parce qu'ils représentent de manière plus efficace la variabilité à petite échelle. Pour des périodes plus longues, la formation et la disparition deviennent plus importantes et les produits obtenus au moyen des modèles numériques deviennent meilleurs. Aucune des méthodes n'est meilleure que les autres; elles devraient plutôt être perçues comme complémentaires, chacune convenant à un moment et à une échelle spécifiques.

EXECUTIVE SUMMARY

This project was jointly sponsored by the Hydrometeorological Research Division of the Canadian Climate Centre, the Central Region of Atmospheric Environment Service, and the Resource Technologies Department of the Alberta Research Council.

The objectives of this study were to assess the need for Quantitative Convective Precipitation Forecasting (QCPF), to review the current research and technological endeavours being carried out in QCPF, and to identify areas of research and development necessary for improving QCPF procedures.

A survey of water resource planners was conducted to determine if a requirement for QCPF existed. The results showed that a need for quantitative convective precipitation forecasting exists in a variety of sectors including agriculture, forestry, construction, urban hydrology, transportation, and public safety. Accurate information regarding rainfall amounts and geographical areas were identified as the two most important forecast products required.

An extensive literature review coupled with a questionnaire and follow-up discussions with scientists and engineers active in the field was conducted to determine the current state of QCPF and identify the scientific and technical requirements to make QCPF a reality. Four approaches have been identified to provide short-term forecasts of mesoscale weather events. The first method, the nowcasting approach, involves extrapolating detailed observed weather patterns. The second approach uses Model output statistics and statistical methods. The third approach uses pattern recognition techniques, or the subjective method used by forecasters. The fourth approach, the dynamical method, involves the prediction of mesoscale events using numerical models.

The key to improving forecasts and warnings of mesoscale weather is a better understanding of the physical and dynamical processes

governing these phenomena. The best way of meeting these requirements is outlined in the following recommendations.

Research into severe convective storms and their relation with larger scale processes, especially those generating localized heavy rainfall, is recommended. Specific geographical areas must be identified for which QCPF's are judged essential. Initially, detailed studies of significant precipitation events in the selected areas should be conducted to help determine time windows and the forcing mechanisms necessary for convection.

The impact of convective storms on local hydrology, especially in an urban environment, should be investigated. Evaluating and understanding the hydrologic responses of a watershed is also required. The development of automated procedures to estimate flooding severity has been identified.

Studies in nowcasting heavy convective precipitation should be conducted. These efforts could adapt or develop methods to extrapolate convective rain fields from radar and satellite observations. One way to facilitate improvements in the nowcasting of convective precipitation on the Prairies would be to carry out a field program in western Canada. The design and conduct of this program could be implemented using SESAME, CASP, and the Limestone Mountain Experiment (LIMEX) as models. Doppler radar, satellite, atmospheric sounding systems, and automated meteorological workstations would play important roles. Participation and involvement in international projects such as STORM is another option to explore.

Studies in mesoscale numerical modelling should be conducted. Initial efforts could adapt existing regional models with mesoscale resolution, parameterized convection, and topography to more effectively reflect local conditions. From the hydrological point of view, it will be important that these studies include the development of coupled hydrological/meteorological models.

Collaboration between research and operational personnel should be encouraged in order to expedite the transfer of QCPF procedures and techniques from the research to operational communities. Avenues to explore include staff exchanges and secondments, assistance to graduate students, and the establishment of a center, including a prototype forecast office, for the study of convective precipitation.

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CHAPTER 1
INTRODUCTION

1.1 Background

Short-term forecasts (0-24 hrs) of the meso to micro-scale structure of weather events embedded within larger-scale systems potentially have a substantial economic impact. Locally heavy rainfalls, ice storms, and wind storms are examples of such mesoscale weather events.

Quantitative precipitation forecasting on the synoptic scale is handled reasonably well by numerical weather prediction models. However, mesoscale convective precipitation events are much more difficult to predict. A considerable research effort will be required to improve the forecasts of the amounts and location of precipitation expected from these storms. In part, due to the recognition of these complexities, the Atmospheric Environment Service's strategic plan calls for improvements to be made in the forecast system's ability to deliver Day-1 mesoscale forecast products.

Quantitative convective precipitation forecasting (QCPF) can be defined as the prediction of localized rainfall duration, amount and areal extent associated with convective weather systems. QCPF outputs are especially important to the improvement of the management of small watersheds and urban areas where the lag time between convective rainfall occurrence and outflow from the basin is short. High rainfall rates over such watersheds located close to densely populated areas can produce hazardous flash flood situations requiring well-integrated warning systems. QCPF procedures are important for the preparation of such warnings. Flood forecasters also require QCPF to address flood threats caused by mesoscale convective complexes covering hundreds of square kilometres. Directly coupling QCPF procedures to hydrologic forecast procedures could produce a generalized rainfall-runoff system and, consequently, good flash flood warnings.

1.2 Scope of Study

As a first step in determining the requirements for research and further technique development, a study was initiated to review the needs for specific forecast parameters and the ability of our current knowledge of convective storms and existing forecast techniques to provide this information. This project was jointly sponsored by the Hydrometeorological Research Division of the Canadian Climate Centre, the Central Region of Atmospheric Environment Service, and the Resource Technologies Department of the Alberta Research Council.

To this end the specific objectives of this study were:

1. To identify and prioritize the needs and requirements of water resource managers and other appropriate groups for quantitative convective precipitation forecasts.

2. To review the current state of scientific knowledge, forecast techniques and technologies related to quantitative convective precipitation forecasting.

3. To identify the best ways of meeting these requirements using existing forecast methodologies and technologies as they apply to the specification of the timing, location, and precipitation amounts and rates associated with convective storms.

4. To specify the scientific and technical questions which must be resolved in order to develop an adequate knowledge base and effective techniques for the provision of accurate and relevant convective precipitation forecasts.

A survey was conducted to determine the requirements of water resource managers for quantitative convective precipitation forecasts and the results are discussed in Chapter 2. A brief overview of the

physical mechanisms involved in convective storm formation and precipitation development is presented in Chapter 3. The present Canadian forecasting capabilities of severe weather including locally heavy precipitation, as well as existing technologies and methodologies, and the scientific and technical requirements for improved nowcasting are reviewed in Chapter 4. The current status of mesoscale numerical modelling for QCPF is reviewed in Chapter 5. The views of experts as determined from a survey trip and from a questionnaire (Appendix D) were integrated into the scientific and technical requirements sections. A summary with conclusions and recommendations for further research that might be undertaken is presented in Chapter 6.

CHAPTER 2
VIEWS FROM WATER RESOURCE MANAGERS

2.1 Introduction

Studies of user requirements play an important role in any effort to improve or enhance the usefulness of weather forecast products. The results from such studies can provide information essential for the design, development and implementation of these products. Murphy and Brown (1982) have suggested that there are two general approaches that have been taken to address the problem of determining user requirements for weather forecasts. These two approaches have been referred to as passive and active. In the passive approach, data related to user requirements are obtained primarily by evaluating the requests for forecasts received from actual and potential users and by analyzing the feedback provided by current users concerning the usefulness and appropriateness of the forecasts. The active approach involves conducting surveys and/or interviews with the relevant users.

An active approach (i.e. survey) was taken to determine user requirements for quantitative convective precipitation forecasts. The specific objectives of the survey were: 1) to identify the current usage and relevant weather variables, the applications, and potential economic value of precipitation forecast information; and 2) to estimate future requirements for quantitative convective precipitation forecasts. Questions were formulated in co-operation with the Hydrometeorological Research Division of the Canadian Climate Centre and the Central Region of the Weather Services Directorate of the Atmospheric Environment Service. Questionnaires were sent out to a wide spectrum of water resource managers in the areas of agriculture, forestry, construction, transportation, urban hydrology and public safety. The list of survey questions is shown in Appendix A.

2.2 Current precipitation forecast usage

Questionnaires were sent to 38 water resource managers, of whom 82% (31/38) responded. An additional 9 unsolicited responses came from users. The excellent response indicates that interest in this type of information is high. The majority of respondents, 65%, (26/40) indicated that they use forecast precipitation information in their activities. They most frequently obtain their forecasts directly from the Atmospheric Environment Service, and have identified rainfall amounts and the geographic area affected as the important information used. Users were asked to rate the accuracy of current forecast products as poor, fair, and good. An objective definition for each rating category was not provided to the users. Consequently, the users' rating are only subjective impressions. The majority of respondents believed that the products they are receiving were fairly accurate, as indicated in Figure 1. The period of the year where the need for which this information is greatest depends on the sector. Agricultural users have identified the growing season, April to October, while the transportation and construction sectors require precipitation information all year round. When it came to estimating the economic value of precipitation forecasts, a majority of respondents found it difficult to provide an estimate. The remainder of respondents estimated benefits ranging from thousands of dollars to several million for agricultural purposes. Respondents did not separate between the effects of the forecast and the effects of the climate or weather on a sector. A summary of current precipitation forecast information usage is shown in Table 1.

The current applications of precipitation forecasts are summarized in Table 2. Agricultural users apply precipitation forecasts for irrigation scheduling, timing of farming operations, crop yield projections, crop quality estimates and drought monitoring. The major construction and transportation application of precipitation forecasts was for scheduling human resource and equipment requirements for building and road maintenance projects. Public safety officials use precipitation forecast information to warn the public and mobilize

emergency response teams in order to minimize loss of life and property damage and to determine disaster assistance eligibility. Hydrologists and city engineers use precipitation forecasts primarily to assess the flooding potential of basins, manage water reservoirs, predict sewer system bypass, forecast daily water consumption and manage urban water distribution systems.

2.3 Requirements for QCPF

The users were asked to estimate (guess at) future requirements for quantitative convective precipitation forecasting by rating the importance of the forecast products as high, medium, and low. The rating indicators were then translated into users' requirements by applying a ranking scheme. A rating of high was assigned 6 points, a medium rating was assigned 3 points and a low rating was assigned 1 point. The total points were added up for each potential forecast product, and a rank assigned according to the sum. Results are tabulated in Table 3. Accurate forecasts regarding rainfall amounts and geographical area were identified as the two most important parameters required.

2.4 Summary

A survey was conducted to determine user requirements for quantitative convective precipitation forecasts. The high response (82%, (31/38)) of the water resource managers responded to the questionnaire, and an additional 9 unsolicited responses were received), indicates that interest in this type of information is high.

This survey suggests that requirements for quantitative convective precipitation forecasting exist in a variety of sectors including agriculture, forestry, construction, transportation, urban hydrology and public safety. Users identified accurate rainfall amounts and geographical area as the two most important forecast products required.

TABLE 1: PROFILE OF CURRENT PRECIPITATION FORECAST INFORMATION USAGE

1. DO YOU CURRENTLY USE PRECIPITATION FORECASTS IN THE CONDUCT OF YOUR BUSINESS OR PROFESSION?

Yes 26 No 13 No answer 1

2. WHAT PRECIPITATION FORECAST INFORMATION DO YOU CURRENTLY USE?

a.	19	Probability of occurrence
b.	23	**Rainfall amounts**
c.	21	Rainfall intensity or rate of accumulation
d.	20	Rainfall duration
e.	23	**Geographic areas affected**
f.	19	Beginning of rainfall (time)
g.	17	End of rainfall (time)
h.	2	Other (please specify below)

- solid or liquid phase
- runoff coefficient

3. WHERE DO YOU OBTAIN THESE FORECASTS?

a.	14	Radio
b.	7	Television
c.	4	Newspaper
d.	19	**Directly from Atmospheric Environment Service** (e.g., via telephone)
e.	0	Consultants
d.	15	Other (please specify below)

- 7 Weather radio
- 2 Alta Env River Forecast Center
- 2 Alta Forest Service
- 4 archived rainfall records

6. WHAT IS THE ESTIMATED ECONOMIC VALUE OF THESE FORECASTS?

Difficult to estimate.

$2.9 million in hay crop benefits

7. WHAT PERIOD OF THE YEAR DO YOU HAVE THE GREATEST REQUIREMENT FOR PRECIPITATION FORECASTS?

April to October

all year round

TABLE 2: CURRENT APPLICATIONS OF PRECIPITATION FORECASTS

- Irrigation requirements or scheduling
- Crop yield projections
- Crop quality estimates
- Timing of farming operations
- Drought monitoring
- Management of water reservoirs
- Assessing flooding potential, staffing and response requirements
- Predicting sewer system bypass
- Forecasting daily water consumption and managing water distribution systems
- Water erosion calculations
- Planning manpower and equipment requirements for summer construction and road maintenance projects
- Planning manpower and equipment requirements for snow removal and road maintenance
- Warning and mobilization of emergency response teams
- Determining disaster assistance eligibility
- Calculation of fire weather indices
- Field research planning
- Service instrumentation
- Research on forecast accuracy and techniques development

Table 3: RANKING USER REQUIREMENTS

	Forecast product	Importance				
		High	Medium	Low	Total	Rank
		(6)	(3)	(1)		
a.	Probability of occurrence	24	10	3	177	3
b.	Rainfall amounts	32	5	2	209	1
c.	Rainfall intensity	17	19	7	166	4
d.	Geographical areas affected	30	6	3	201	2
e.	Beginning of rainfall (time)	14	11	10	127	5
f.	End of rainfall (time)	9	11	14	101	6
g.	Other (please specify below)	2	1	0	15	7

- lightning
- resolution

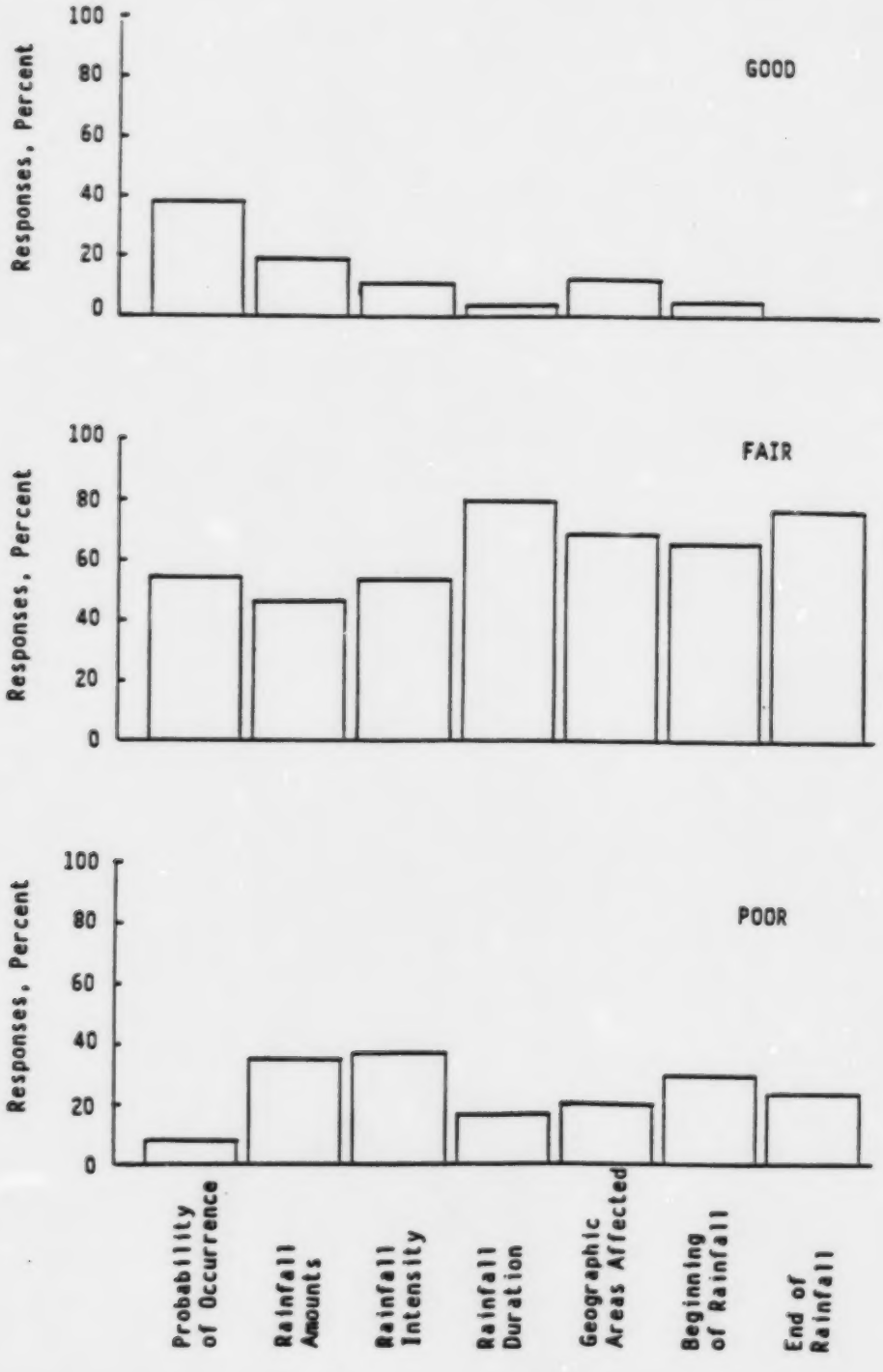

Figure 1: Accuracy of precipitation forecast products as subjectively assessed by the 26 water resource planners who indicated that they currently use precipitation forecast products.

CHAPTER 3
PHYSICAL MECHANISMS AND CONVECTIVE PRECIPITATION

3.1 Introduction

Precipitation is important because it is the primary source of water. At the same time it poses a forecasting problem because it often arrives in storms, which are sporadic, difficult to predict, and sometimes violent. An understanding of the precipitation-producing storms is therefore required to facilitate detailed short-term weather forecasts. However, understanding atmospheric precipitation processes has been elusive because the temporal and spatial scales involved in the development of precipitation, cover a wide range from the sub-cloud scale to the synoptic scale.

This chapter will provide a brief overview of precipitation formation and the physical mechanisms involved in the production of significant summertime precipitation.

3.2 Precipitation formation

An important advance in the understanding of microphysical processes leading to the formation of precipitation in cyclones was made by Bergeron (1935), who proposed that most of the precipitation in these storms originate as ice crystals in clouds. According to this hypothesis, ice crystals are nucleated in a much larger population of supercooled droplets at temperatures below about -10°C. Since the saturation vapour pressure in a mixed cloud which is dominated by supercooled droplets is in excess of ice saturation at the same temperature, the ice crystals grow rapidly by vapour deposition while nearby droplets evaporate. In this way a single crystal can acquire the mass of many droplets.

The physical mechanisms of precipitation development are more

complex. In addition to the ice crystal mechanism, we now recognize that drop collision and coalescence often play an important role in rain formation.

3.3 Physical mechanisms

During the warmer half of the year, precipitation over midlatitude land masses is dominated by deep convective events, collectively referred to as thunderstorms (Houze and Hobbs, 1982). In sufficiently moist and unstable air, convective clouds can grow to great heights, develop vigorous updrafts, and produce heavy rain, lightning and hail. The trigger mechanism needed to start air moving upward may be the unequal heating of the surface, the effect of terrain, the lifting of warm air along a frontal zone, or convergence lines in the boundary layer. Diverging upper-level winds also provide a favourable region for thunderstorm development. Usually several of these mechanisms work together to generate severe storms. These large severe storms may occur individually, or more typically, in groups associated with synoptic-scale fronts or mesoscale convergence zones.

Extensive studies over the last three decades by means of radar, surface and upper-air networks, and instrumented aircraft have made it possible to describe thunderstorm structure and development and to recognize the meteorological conditions under which they occur. The Thunderstorm Project (Byers and Braham, 1949) showed that thunderstorms consist of individual cells which go through a lifecycle from initiation, to maturity, to decay. An organized multicell storm differs from an air-mass storm in that it occurs in an environment of substantial wind shear. As a result, the cells form and move through the storm in a systematic rather than random way. The most severe thunderstorm is the so-called supercell thunderstorm (Browning, 1964). Its cloud structure, air motions, and precipitation processes are dominated by a single storm-scale circulation consisting of one updraft-downdraft pair. A summary of the dynamics and structure of severe hailstorms is presented in Marwitz (1972 a,b,c).

Where conditions are favourable for convection, a number of individual thunderstorms will occasionally grow in size and organize into a large convective weather system. The storms comprising such a complex typically share a common upper-level cloud shield which appears very prominently in satellite imagery when the system matures. Maddox (1980) has used this fact to define a Mesoscale Convective Complex (MCC). Fritsch et al. (1981) have presented evidence that a significant portion of the summer rainfall in the Great Plains and Midwestern United States are attributable to MCCs. The main synoptic conditions favourable for MCC development have been identified by Maddox et al. (1986). MCC's are a fairly rare phenomenon over Canada (Legal, 1988a), however, on July 31, 1987, a severe rainstorm moving across southern Manitoba and into northwestern Ontario, was identified as an MCC.

3.4 Summary

The greatest amounts of summertime precipitation come from convective clouds. Production of significant amounts of precipitation involves interactions of physical systems of three different scales: a) large-scale atmospheric motion systems, b) clouds and mesoscale systems, and c) cloud particle systems. An understanding of scale-interactions and the physical mechanisms of precipitation development is still needed.

A required step towards substantially improving objective forecasts of significant summertime precipitation, is to determine the mechanisms, and their relative contributions, for producing significant summertime precipitation. Colquhoun (1987) has developed a decision tree method, based on physical reasoning, to forecast thunderstorms, severe thunderstorms and tornadoes. Heideman and Fritsch (1988) subjectively determined the primary forcing mechanisms using satellite, radar, surface, and upper-air data from the June-August periods of 1982-1983 in the United States. They ascribed all significant summertime precipitation to one or more of 12 forcing mechanisms. The mechanisms were divided into three groups. Group A

mechanisms were associated with extratropical cyclones (cold-, post cold, warm-, and stationary frontal forcing). Group B mechanisms represented mesoscale forcing (convective feedback, short wave in warm air, sea breeze, old boundary, and dryline) features. Group C mechanisms included orographic and tropical systems.

CHAPTER 4
NOWCASTING APPROACH TO QCPF

4.1 Introduction

Weather phenomena on the mesoscale are the primary subjects of nowcasts. The term nowcasting symbolizes an observations-intensive approach to local weather forecasting using current data made available through remote sensing capabilities. Browning and Golding (1984) have defined nowcasting as the extrapolation or advection of detailed weather patterns for periods of zero to four hours. When dealing with convective precipitation, nowcasting may also involve the use of radar extrapolation techniques, satellite schemes, rainfall detection and quantification techniques, manual systems, or the use of automated systems.

This chapter will review the current Canadian activities related to nowcasting, provide an overview of nowcasting approaches being used in the United States and other countries, and discuss the scientific and technical requirements for improved QCPF from the nowcasting perspective.

4.2 Current Canadian nowcasting activities

There are two distinct aspects to forecasting severe weather. The first aspect is concerned with assessing the environmental conditions conducive for storm development, while the second aspect deals with the detection, monitoring, and short-range forecasting of severe storms.

Heightened interest in summer severe weather forecasting in Canada began in the early sixties as the National Severe Storms Forecast Center (NSSFC) became an important part of the U.S. National Weather Service. Severe Weather Programs have evolved at the Prairie Weather Centre in Winnipeg, the Ontario Weather Centre in Toronto, the Quebec

Weather Centre in Montreal, and at the Alberta Weather Centre in Edmonton (Legal, 1988b).

4.2.1 Severe storm forecasting capabilities in Canada

Presently, only qualitative convective precipitation forecasts are directly issued through the AES Severe Weather Programs. Heavy rains are indirectly forecast as part of severe thunderstorm and tornado watches and warnings.

Assessing the potential for mesoscale convective weather involves the analysis and diagnosis of dynamic and thermodynamic fields. Severe thunderstorm forecasting essentially tries to identify the time and place where unstable (or destabilizing) air, moisture, synoptic-scale lift aloft, and low-level convergence coexist. This approach (Miller, 1972) has been used in most of the severe weather centers. The technique involves analyzing a number of surface, upper-air, and thermodynamic charts and preparing composites to subjectively determine the location and potential for severe weather. Some types of severe weather, including weak windshear tornadoes, waterspouts, some heavy rains and hail, and strong non-tornadic winds due to fast-moving thunderstorms or microbursts, exhibit different dynamic and thermodynamic factors and thus do not fit this classical approach. Therefore, supplementary approaches have been incorporated to assist in severe weather forecasting.

The Prairie Weather Centre severe weather program also includes an automated radar acquisition and display system, and a weather watch network. The acquisition of the King City Doppler radar information for operational forecasting at the Ontario Weather Centre has improved the warning service provided to the public. At the Quebec Weather Centre, radar-based severe weather criteria were developed very early on (Marois, 1977). More recently, a summer severe weather index, hail analysis routine, hodograph fitting routine, and moisture convergence charts have been developed and implemented into their operational forecasting program. The new AES prototype Radar Display Processor

(RDP) has been employed by their program since 1987. The Alberta Weather Centre relies on satellite imagery to supplement severe weather diagnosis and analysis because the upstream mountains limit the usefulness of conventional and radar observational data (Bullas, 1986). The Synoptic Index of Convection (SC4), originally developed and used successfully as a point index for predicting hail size for the Alberta Research Council Hail Project (Strong, 1979), more recently has been modified as an area predictor for convectively complex initiation, movement and maximum intensity (Strong, 1986). Currently, the SC4 is being tested as part of an Artificial Intelligence prototype convective forecast system (SWIFT). TOVS (Tiros Operational Vertical Sounder) data of temperature and moisture have also proven to be useful in some instances (Goodson, 1988). Further testing and evaluation is underway at the Alberta Weather Centre.

4.2.2 Remote sensing capabilities in Canada

Weather radar provides an important capability for detecting, tracking and monitoring the development and subsequent motion of severe convective storms. The United States National Weather Service primarily uses 10-cm (S band) wavelength radar because it experiences less attenuation by intervening heavy rainfall. In Canada, the Atmospheric Environment Service uses the 5-cm (C band) wavelength radar because it is believed that thunderstorms in Canada have generally lower liquid water contents and because this wavelength is better suited for detecting snow. The current Canadian weather service radar network is shown in Figure 4.1.

The current level of signal processing from Enterprise CWSR81 radars used by AES produces digital plan position indicator (PPI) images. The Alberta Weather Centre, the Prairie Weather Centre use a system originally developed at the PRWC, to automatically dial and display Enterprise images. Up to six images from one radar or different radars can be displayed at the same time. The system can also loop up to six images to provide animation. Construction of

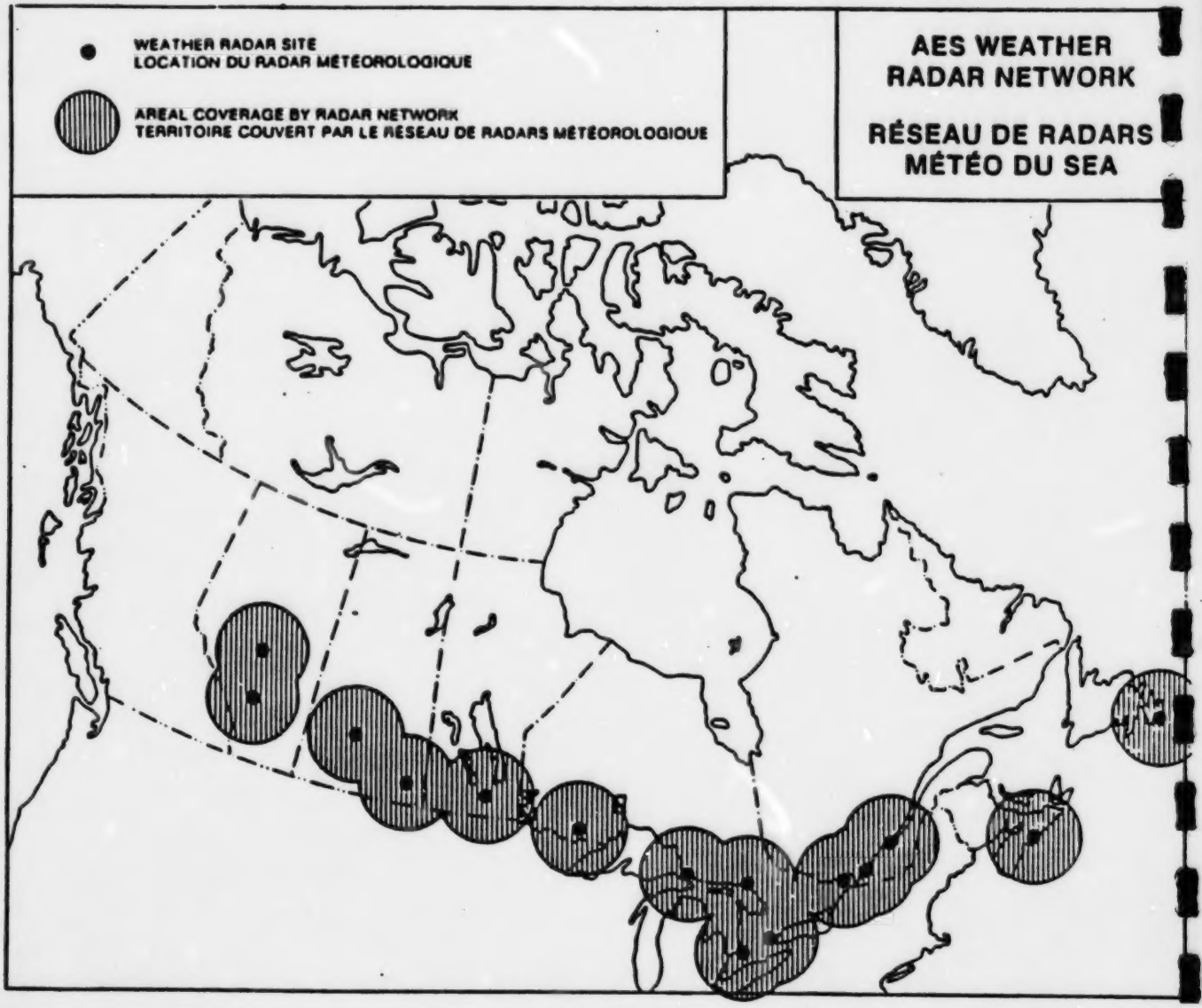

Figure 2: AES Weather Service Radar Network.

three dimensional views of storms requires manual intervention to change antenna elevation angles. Such changes are operationally awkward and tedious.

AES also has SCEPTRE 5-cm full volume scan radar data processing capabilities. Data are processed at the site into constant altitude PPI (CAPPI) images and transmitted for operational use as an analog signal to facsimile recorders at the weather centres. CAPPI images are an improvement over PPI images as they can readily provide three dimensional storm structures. However, the cycle times of the radar are too long, and the flexibility for production of special forecast tools, such as storm cross sections, is very limited.

The King City weather radar is the AES Doppler research radar (Crozier et. al., 1989). It is a part of the Canadian operational weather radar network. In addition to its atmospheric research program, radar observations are provided to the operational forecast sector. This facility is a C-band Enterprise radar with a ten minute data collection time in which it samples in the Doppler mode and in full volume reflectivity mode. It provides conventional CAPPI, maximum reflectivity, echo top, and PPI radial velocity images as well as a number of other specialized products to the Ontario Weather Centre. All processing is done at the King City site and data products are transmitted by telephone lines to a number of users. Data and products are archived on magnetic tape.

McGill University operates a 10-cm research radar at Ste. Anne de Bellevue on Montreal Island. The university has recently completed the Radar Display Processor (RDP) prototype for AES. This prototype has been in use in the Quebec Weather Centre since the summer of 1987. Full volume radar data is transmitted to the RDP located in the Weather Centre where it can be manipulated into many different radar products. An RDP has also been implemented for the AES Elbow Radar site in Saskatchewan in the summer of 1989. This facility will be used for operational forecasting by PRWC, and for research by the Hydrometeorological Research Division.

The Alberta Research Council maintains an unmanned weather radar site at the Red Deer Industrial Airport. This site has served as the center for severe storm research in Alberta for over 20 years. The facility contains a unique circularly polarized 10 cm S-band radar and a 5 cm C-band facility. Both radars are Enterprise systems. Presently, limited research is being carried out. Plans call for Dopplerizing the 10 cm radar for use in the detection of severe storms beginning in 1989 or 1990.

4.3 Remote sensing applications

Weather radar and satellite systems in the form of PPI displays of radar reflectivity, or as photographic images of cloud infrared emission or visible albedo, have been traditionally used as part of weather forecasting, particularly nowcasting. Although these images have provided additional information for the forecaster, their direct use as a prediction tool have been limited.

Techniques have been developed for using radar and satellite data to predict rainfall rate, thunderstorms or possible flooding situations. A number of these techniques will be highlighted and reviewed.

4.3.1 Radar extrapolation schemes

A technique for the short-term forecasting of rainfall using radar was initially developed by Austin and Bellon (1974) at McGill University. Their forecast procedure consisted of making digital CAPPI Cartesian maps and computing the velocity of the precipitation pattern on two maps by locating the maximum cross-correlation coefficient. The forecast was then obtained by translating the entire pattern in the direction of the computed motion (Bellon and Austin, 1978). They showed that the major cause of poor nowcasts was not due to errors in the forecast displacement, but to the unpredictable configuration of radar echo patterns as the convective cells undergo development or decay during the forecast period.

Bellon and Austin (1984) examined the accuracy of quantitative radar rainfall forecasts for a duration of less than or equal to 3 hours. A data base of 37 weather sequences, totalling 200 hours of data from four years, was used to evaluate radar precipitation forecasts using a cross-correlation forecasting scheme verified over an urban catchment area of 600 km^2 equipped with an array of telemetered rain gauges. Interest lay in determining the components of the total forecasting error, namely, a) the error resulting from the limited rainfall measuring accuracy of the radar, and b) the error due solely to the forecasting technique. They found that the radar-derived accumulations have an inherent error of the order of 25%, 0.5-hr forecasts have an error of ~50% and 3-hr forecasts have an error of 60%. Since radar measurements of accumulation have inherent errors of the order of 25% over the test region, it was concluded that the forecast procedure introduced an additional error of the order of 35%. It was found that the introduction of a calibration adjustment for each case did not significantly reduce the forecast errors, since they were mainly due to the unpredictable nature of storm development and growth.

The British Meteorological Office (Browning et al., 1982) examined the feasibility of quantitatively forecasting hourly rainfall for lead time periods of 0 - 6 h ahead using linear extrapolation techniques. Data in the form of composite maps of processed digital rainfall information from a network of four weather radars were used in this study. Forecasts were derived both subjectively in real time and objectively using an echo centroid tracking technique (Barclay and Wilk, 1970), for a total of 29 frontal rainfall events. The objective technique produced forecasts on a grid of 32 by 32, 20 km square areas. The subjective technique was applied to a single target area in order to investigate some of the sources of error and their impact on forecasts. The results showed that radar rainfall measurement errors accounted for as much as half of the errors in the forecasts. The authors attribute the relatively high error to a variety of causes, including development or decay of rain areas, overshooting of low precipitation by the radar beam, incorrect translation vectors,

radar calibration changes and bright band effects.

In examining the accuracy of quantitative rainfall forecasts, the errors, both in millimetres of rain and percentage, for the objective forecasts were seen to remain fairly constant with time at - 75%. The subjective forecasts showed a slight increase with forecast lead time (45 - 50% in the first 2 hrs to 50 - 55% thereafter). The authors suggest that significant improvements in forecast accuracy may be achieved if the forecaster is able to exercise his judgement in the analysis and quality control of the radar data before they are input into an objective forecasting routine. Further improvements can be achieved by subjectively adjusting the motion of the rainfall pattern at the output stage of the forecast but these improvements appear to be smaller than those achievable by a careful analysis of the input data.

In an absolute sense the results from the Canadian and British studies seem of relatively low accuracy. On the other hand, it may be that for some purposes these quantitative precipitation forecasts are much better when compared with the forecast of "a chance of showers this afternoon". Both studies indicate that the main challenge lies in improving our understanding of the structure of mesoscale precipitation systems and their interaction with the synoptic scale.

4.3.2 Satellite precipitation estimation techniques

Several satellite precipitation estimation techniques ranging from fairly simple (bulk statistics schemes) to very sophisticated (cloud tracking schemes) exist. These are summarized by the WMO (1985), as follows:

a) **Bulk Statistics Methods** (e.g., GOES Precipitation Index, GPI), The simplest of the satellite estimation techniques, use the statistical properties of cloudiness in the boxes or areas in which precipitation is to be estimated.

b) **Isolated Cloud Schemes** utilize the full spatial resolution of the imagery but ignore inherent temporal information (e.g., cloud growth information) which is incorporated in the life

history schemes or cloud tracking schemes. Rainfall is essentially inferred from a single satellite image once clouds have been identified and isolated. Generally, the schemes have been applied to summer time convection. Performance degraded when applied to autumn and winter systems.

c) **Cloud Tracking or Life History Schemes** focus on the smallest space and time scale of convection. Most techniques identify clouds from geostationary satellite images, and track the clouds with time through a sequence of images. The Convective Infrared Satellite Technique (CIST; Griffith et al, 1978) is an example of a computer-automated method that has been applied in a research mode to a number of locations of varying time and space scales. The most extensive statistics on error assessments and sampling requirements exist from this technique.

The Canadian RAINSAT system for the analysis and short-range forecasting of precipitation has been running in real-time since September, 1984, transmitting maps to the Centre Meteorologique du Quebec in Montreal (King and Yip, 1987). It was developed by Austin and co-workers at McGill University as a means of estimating where precipitation is falling beyond radar range, for forecasting its movement. The RAINSAT computer system receives digital GOES visible and infrared images each half hour, and radar data every 10 min from the AES King City radar and the McGill radar.

RAINSAT uses navigation information included with the GOES IR image to remap the VIS and IR data to a Lambert conformal projection for the Great Lakes/St. Lawrence basin. The remapped infrared (IRMAP) and the remapped normalized visible (IRMAP) maps are used to construct a probability of rain analysis (PRMAP) map. The RAINSAT probability of rain relationship is calculated by comparing remapped GOES satellite data for a given half hour with the corresponding radar data. Two consecutive PRMAPs are used to produce a forecast (FORMAP) map.

Verification of RAINSAT probability of rain maps with radar and surface data indicate useful skill in estimating rain areas. The main skill lies in identifying regions that are clear, cloudy with a low probability of rain, and cloudy with a significant probability of rain.

The Canadian Climate Centre has been developing a system to integrate satellite, radar, and ground based data into an objective rainfall analysis system. Scientists there have evaluated three techniques developed by Negri et al (1984), Lovejoy and Austin (1979), and Barrett (1970). Trials conducted under spring weather conditions indicated that the methods have skill for estimating daily and monthly rainfall. They also showed that a simple climatological technique (Barrett, 1970) was as good as two other more complex models. Plans are to test the methods during the summer when convective rain dominates (Hogg et al., 1988).

Bellon and Austin (1986) compared the relative accuracy of satellite and raingage rainfall measurements over middle latitudes during daylight hours. Their satellite rainfall estimation technique is based on the assumption that clouds which are both high and of large vertical extent are more likely to be raining (Lovejoy and Austin, 1979). Radar rainfall observations are used as the ground truth with which satellite data are calibrated. Satellite methods tested were not skillful in delineating instantaneous high rainfall rates, but were relatively accurate in delineating areas above a low rainfall threshold of 2 mm during daylight hours.

In a separate comparison of satellite and gauge rainfall estimates, Griffith (1987) points out that satellite estimates are area averages and not point estimates. However, it appears that human judgement, higher-resolution IR data, and the inclusion of the visible channel data, improve satellite-based estimates of rainfall. She found little difference between the life history and streamlined techniques, suggesting that the additional complexity of the life history scheme is not necessary.

The Synoptic Analysis Branch of NOAA/NESDIS has a Quantitative Precipitation Estimates program which sends precipitation estimates for heavy rain and snow over the U.S. mainland on AFOS messages (Borneman, 1987). The rainfall estimation technique uses an empirically-derived decision tree, and relates satellite half-hourly

cloud top temperatures and cloud top growth to maximum half-hourly rainfall amounts. Rainfall estimates are also adjusted for overshooting tops, convective cluster and line mergers, the saturated environment with stationary storms, divergence aloft, low-level inflow, storm movement, and available moisture. Details are described in Scofield (1987). These precipitation estimates show a strong tendency to overestimate for smaller amounts and underestimate for larger amounts.

Shi and Scofield (1987) describe a 3 to 12 hour convective heavy precipitation index for the amount of rainfall that occurs from a mesoscale convective system (MCS). This index depends on an instability burst factor (the local change of stability with time), available moisture, type of MCS propagation (backward or forward movement), and location of the large scale and small scale upwind vertical motion areas. The positive advection of θ_e and the maximum values of θ_e associated with surface convergence proved most useful in determining where MCSs will develop and propagate.

4.3.3 Rainfall Quantification Techniques

In addition to the RAINSAT technique previously discussed, the South Dakota School of Mines and Technology has developed a rainfall quantification technique called the Area-time-integral (ATI). The ATI technique provides a means of estimating total rain volumes over fixed or floating target areas of the order of 1,000 to 100,000 km^2 for radar echo clusters lasting more than 40 minutes (Doneaud et al., 1981, 1984). The technique does not require consideration of echo structure as measured by radar to generate the rain volume estimates; only the area covered by rain events is needed.

In a later investigation (Doneaud et al., 1988), a modified ATI technique was used for nowcasting total rain volume. The radar ATI was calculated using maximum area, maximum reflectivity, and maximum echo height of the convective event as the ending time of the analysis; the rainfall volume was computed for the lifetime of the

storm. This technique creates an opportunity for nowcasting convective rain volumes with a lead time of 10 min - 2 h or more.

The NEXRAD hydrometeorological software (NEXRAD Project Office, 1988) provides quantified estimates of convective rainfall from radar measurements. The various algorithms for NEXRAD are summarized in Appendix E.

Preliminary evaluations have been conducted on the NEXRAD algorithm series (PROFS Project Office, 1988). In general, the results suggest that the NEXRAD precipitation algorithms seem to detect areas of rainfall adequately, and often have been fairly accurate in estimating rainfall maxima. It is also very important for this algorithm series to be able to make good precipitation estimates in mountainous regions. A routine for interactively editing definitions of sectors over mountainous terrain was developed so that radar sectors were well above areas subject to spurious rainfall accumulations. This semi-automated scheme resulted in excellent rainfall estimates in the mountains of Colorado. Problems of anomalous propagation (AP), clutter, and other non-weather echoes were not noticeable during the PROFS evaluation. However, AP is rare in the area tested and this result should not be generalized. Hail contamination and bright band effects did pose serious problems.

4.4 Automated systems

Nowcasts are by their very nature highly perishable. The mesoscale observation systems provide an enormous data base, and new sensing systems will continue to augment this information base. It is important for the meteorologist to be provided with the necessary facilities to manipulate, diagnose, analyze, and disseminate large data sets very rapidly if the nowcasts are not to lose their value. Advances in information technology and telecommunications permit rapid dissemination and new methods for data presentation to the user. A meteorological workstation (interactive video display) enables the meteorologist to combine data streams, replay action sequences (radar,

satellite, surface mesonets, etc.), and amend observations and forecasts on a common scale and map projection. Efforts have been underway to develop automated systems. Three examples are provided which illustrate the potential of these systems.

4.4.1 CASP Forecast Centre

The Canadian Atlantic Storms Program (CASP) (Stewart et al. 1987) was a major experiment designed to improve the understanding and prediction of winter storms affecting the Canadian Atlantic coast. During CASP a dedicated forecast center conducted experiments in mesoscale forecasting. Precipitation forecasts prepared at the CASP Forecast Centre (CFC) were found to be significantly better than standard AES forecasts (MacDonald et al., 1988). This improvement was attributed in large part to the fact that forecasters at CFC used a McIDAS workstation, but also that they were concentrating more at the mesoscale for more limited areas than the official forecaster's area of responsibility.

The McIDAS (Man-computer Interactive Data Access System) workstation from the University of Wisconsin (Suomi et al., 1983) was set up for a number of specific applications during CASP. Six predefined satellite animation sequences (loops) were created and continuously updated. These comprised images from the visible, infrared (11 μm), and water vapor (6.7 μm) channels from the geostationary (GOES) satellite. Imagery distortion problems were overcome by programming McIDAS to remap certain sets of visible and infrared images to a polar-stereographic projection. Examination and comparison of the enhanced visible and infrared images and loops provided a very reliable means of estimating precipitation occurrence for areas beyond radar coverage.

4.4.2 FRONTIERS

FRONTIERS (Forecasting Rain Optimized using New Techniques of Interactively Enhanced Radar and Satellite) is an interactive system, developed by the British Meteorological Office, allowing a forecaster to blend data from a network of weather radars and Meteosat, so as to generate frequent analyses and forecasts of the precipitation distribution (Conway, 1987). Every half-hour, analyses and forecasts of rainfall covering a three-hour period are produced by the linear extrapolation of recent movement of rainfall areas. The FRONTIERS operator divides the rainfall field (a merger of satellite-derived rainfall and quantitative radar rainfall) into a number of clusters to which he assigns independent velocities. FRONTIERS then computes the forecast rainfall by moving the clusters with their assigned velocities. Very detailed site-specific forecasts can be derived using this approach but their accuracy falls off rapidly with forecast period.

As a complement to the FRONTIERS nowcasting method, a dynamical method which uses a primitive equation model with a horizontal grid length of about 10 km is also employed. This model is initialized using a combination of forecast fields from a model of lower resolution and recent observational detail from a variety of sources. These inputs are reconciled by means of near-continuous assimilation. Resulting mesoscale forecasts take into account development and decay. Compared with the forecasts prepared using the nowcast method, however, they suffer from being based on less recent data and also from a degradation in spatial resolution.

4.4.3 DAR^{3}E

Nowcasting also requires the ability to integrate many data sets. An example of such a capability is described. The Denver Advanced Weather Interactive Processing System for the 90's (AWIPS-90) Risk Reduction and Requirements Evaluation (DAR^{3}E) system was developed by

NOAA's Program for Regional Observing and Forecasting Services (PROFS) to give forecasters access to newer and more extensive information than before. The DAR^{3}E workstation acquires data from many sources (including conventional and Doppler radar, surface networks, atmospheric soundings, and satellites) to give the forecaster a more complete and accurate picture of synoptic, and mesoscale weather conditions. It has over 300 AFOS graphics incorporated into its advanced meteorological workstation.

DAR^{3}E supports prediction of severe weather events in the 0 - 12 hour range. One of the most important features of DAR^{3}E is the automatic generation of severe thunderstorm or tornado warnings. For example, a forecaster looking at the radar screen can see a severe weather event developing and use the cursor to draw a box around the area affected by the storm. A tornado or severe weather warning is generated and presented to the forecaster for review. With the latest text facility, it is possible to prepare forecasts in one window and issue severe weather warnings from another at virtually the same time. Two prototype facilities, one at the Denver weather center and the other at PROFS in Boulder, are currently issuing severe weather forecasts. Evaluations are underway.

4.4.4 Examples from the Private Sector

The City of Tulsa, Oklahoma has developed a state-of-the-art flash flood warning system (City of Tulsa, 1988) with the aid of the private sector. This system is a fully-integrated one composed of weather radar, meteorological and streamgauge networks, hydrologic models for 14 flood-prone drainage basins, a centralized communications and control center, and a 62 siren outdoor warning system.

Henz and Kelley (1986) describe a flash flood prediction scheme developed for Phoenix, Arizona. Through the use of the HKA Excessive Convective Rainfall Model they integrate hydrological and meteorological data to make regional and local assessments of flash flood potential. Threat levels are identified and messages are sent

to appropriate departments (e.g., fire, police, and street maintenance). As convective storms approach, messages are sent predicting likely effects on various canals, streets, and basins. Presently basin-specific, storm-specific convective rain forecasts are produced for the Colorado Urban Drainage and Flood Control District.

4.5 Scientific and Technical Requirements

Doswell and Maddox (1987) discuss the practical realities of quantitative precipitation forecasting. They cite QPFs as most essential to issuing flash flood watches. Such QPFs require the forecaster to combine hydrological with meteorological considerations. Doswell and Maddox point out that any QPF product now or in the foreseeable future, does not purport to predict actual rain gauge measurements. Even the most diligent forecaster is unlikely to hit every mesoscale QPF with enough accuracy and lead time to satisfy the hydrologist's needs. Doswell and Maddox (1987) suggest that for improved QPF there is a scientific requirement for physical (i.e., conceptual or qualitative as opposed to numerical) models to be used to:

a) Refine estimates of when and where precipitation probabilities are enhanced or diminished, or to

b) Suggest the likelihood of precipitation reaching significant thresholds.

The fundamental area in need of further research concerns storm initiation. Before the storm has formed, the problem is to decide where it will form. Specific questions raised include: What determines the locations of initial convective development? Can initiation be forecast? What is the inherent predictability of convective systems? Research into the correlation of observed surface convergence to thunderstorm growth (Garstang and Cooper, 1981), the initiation of convective storms at radar-observed boundary layer convergence lines (Wilson and Schreiber, 1986) is required.

Wilson and Schreiber (1986) and Purdom (1982) anticipate major

advances in the 0 - 2 hour time frame, provided that Doppler radar data for detection and monitoring convergence lines is integrated with high resolution satellite data to monitor cloud growth, and surface and upper-air data to estimate atmospheric susceptibility to deep convection. These two papers identify needs for research into the following:

a) The creation of a particular intense or sustained updraft associated with a convergence line-related kinematic feature.

b) The collision of convergence lines.

c) The intensification of existing clouds when a boundary passes under them.

d) A boundary encountering a localized relatively unstable air mass.

e) The interaction of a boundary with a range of hills or mountains.

An understanding of the influence of spatial variability in land use, soil moisture, and terrain and their interactions with propagating synoptic disturbances is also required. How important is soil moisture in controlling convective precipitation?

Once the storm has formed, an important scientific problem is to relate radar reflectivity or the behaviour of clouds (as viewed by satellite) to rain rate. What environmental factors and microphysical factors are important in determining convective precipitation rates and durations? Radar data usually are obtained by scanning in azimuth at a low elevation angle and making measurements at discrete intervals of range and angle. Reflectivity factor values are converted to rainfall rate with an appropriate Z-R relationship and accumulated in time to provide rainfall depth. For operational forecasting of river flow and flash floods, dense rain gauge observations are desirable, but their installation has not been practical.

Numerous factors can cause errors in radar rainfall measurements. These factors can be categorized as a) errors in estimating radar

reflectivity factors, b) variations in the Z-R relationship, and c) gauge and radar sampling differences. Errors in estimating radar reflectivity factors include; beam blockage by ground clutter, anomalous propagation (bending) of the radar beam, and attenuation by precipitation, cloud and atmospheric gases, (mostly affecting the shorter wavelengths). Contributing error sources identified in gauge measurements include; adhesion or gauge wetting, inclination of the gauge, splash into and out of the gauge, evaporation and airflow around the gauge. Hydrologists and meteorologists have resorted to a network of raingauges and radar to improve areal average rainfall estimates.

Further studies to improve the Z-R relationship in radar rainfall estimates are required. The following require further investigation: the effects of precipitation drift, variations in drop-size distributions, variations in vertical air motions, hail contamination, and Z-R relations that actually vary widely from storm to storm and as precipitation regimes evolve through the day.

A further requirement for improved radar rainfall estimates is a solution to the sampling problems associated with radar - raingauge comparisons. Further evaluation of the following topics have been identified:

a) The effects of precipitation drift and vertical air motions on the radar bias computation procedure. The radar bias computation is designed to correct large errors in the radar-derived rainfall estimate by using raingauge data as ground truth.

b) The effects of raingauge measurement errors.

c) The effects of raingauge density and undersampling of convective rainfall.

d) Techniques to compute non-uniform bias.

e) Variational analysis techniques to integrate radar and raingauge estimates.

f) Methods to determine optimal settings of adjustable parameters in the radar bias computation procedure.

The PROFS Project Office also recommends that the use of differential reflectivity to improve rain rate estimates be investigated as a possible expansion of NEXRAD capabilities. Differential reflectivity is defined as the ratio of a reflectivity measurement at horizontal polarization to that at vertical polarization. One additional major improvement that could be realized through the use of differential reflectivity is the determination of areas contaminated by hail and what reflectivity levels correspond to hail areas.

From a hydrologist's perspective, Stewart (1987), identifies a scientific requirement for the evaluation and understanding of hydrologic responses of a watershed. Urbanization and changing land use are critical factors in estimating a basin's response to rainfall and projecting future runoff conditions. Basin size, shape, soils, and existing hydraulic features are other key considerations.

From a flood forecasting perspective, Stewart (1988) states that an emphasis should be placed on identifying the start time for peak rainfall. He indicates that simplified decision aids can and should be developed to provide a means for estimating flood severity quickly.

The fundamental objective of the AES and Weather Service Office (WSO) Workstation Project is to develop, prototype, and implement an interactive, computer-graphics workstation. Such an effort addresses the need for a fully-integrated system (i.e., a full-function workstation) which has been pointed out by MacDonald et al. (1988) following forecasting experiments during CASP, by Doswell and Maddox (1987), by the PROFS Project Office (1988), and by many others. An additional point regarding meteorological workstations made by Schlatter (1987) and others is the need for a capability to manipulate data streams at the local level to permit generation of special displays and forecast products vital to local concerns.

A further technical requirement related to data acquisition and dissemination is the need for telecommunications technology capable of

distributing all meteorological and hydrological guidance products and data in a timely and efficient manner (Schlatter, 1987). Efficient data acquisition and analyses will also require the use of automated techniques (i.e., artificial intelligence and knowledge-based systems) (Doswell and Maddox, 1987).

Currently, the U.S. National Weather Service is in the midst of a major modernization program whose goal it is to provide more timely and accurate mesoscale forecasts with improved cost effectiveness (Schlatter, 1987). Improved warnings for hazardous weather of all kinds will receive special emphasis. To meet the technical requirements for such improved forecasts and warnings, a major upgrade of communications and display capabilities is included in this modernization plan. This upgrade is the AWIPS-90 and AWIPS-II systems. These systems are expected to:

a) Integrate radar and satellite data with current conventional data,

b) Allow for substantially expanded local applications processing,

c) Provide for distribution of all meteorological and hydrological products and data, and

d) Employ a system architecture that can accommodate growth.

CHAPTER 5
NUMERICAL MODELLING APPROACH TO USEFUL QCPF

5.1 Introduction

Although conceptual models are important in our understanding of the structure and evolution of mesoscale phenomena, numerical models are the primary tools to test and quantitatively interpret and integrate the complex physical and dynamical processes that interact to produce mesoscale phenomena.

Current operational numerical models provide valuable guidance to forecasters on the synoptic-scale (characteristic wavelengths greater than 2500 km). Over the years there has been a steady improvement in the prediction of large-scale wind and pressure patterns. This improvement can be attributed to higher vertical and horizontal resolution, increases in domain from hemispheric to global, and improvement in analysis and initialization techniques and physical parameterizations. Improving the prediction of precipitation, on the other hand, has been slower (Ramage, 1982), primarily because precipitation exhibits greater variability on scales much smaller than the synoptic scale.

This chapter will review the current Canadian activities related to mesoscale modelling, provide an overview of models currently being used in the United States and other countries, and discuss the scientific and technical requirements for improved QCPF from the numerical modelling perspective.

5.2 Current Meteorological QPF Procedures

Current operational QPF procedures over a certain area are based on:

a) The use of large scale models that simulate atmospheric dynamics, with spatial resolutions on the order of 150 km grid size

b) The use of statistical regression models that correlate the predictions of the large-scale atmospheric models with observations on a smaller scale, and

c) The experience of forecasters with local weather patterns and topographical effects.

5.2.1 Canadian QPFs

There are three quantitative precipitation forecasts produced operationally by the Canadian Meteorological Centre (Toth, 1988). They are the HRV9 spectral model, the regional finite element model RFE, and the diagnostic QPF.

The diagnostic model (Kirkwood, 1977) is driven by the spectral model. Computations of precipitation amount are performed, between initial time and 36 hours, on a diagnostic basis at each grid point given the spectral model forecasts of temperature, winds, vertical velocity and dew point depression. There are two quasi-independent formulations within the diagnostic model (Davies et al., 1973). The first of these is designed to deal with precipitation associated with synoptic features in the circulation pattern. The second is used to forecast the smaller scale activity and includes separate parameterizations for frontal showers and air-mass showers.

The spectral model is a primitive equation, 15 level with sigma coordinate vertical resolution, and spherical harmonics (59 waves) horizontal resolution and parameterized physical processes. Initially, the dry and moist convective adjustment schemes (Manabe et al, 1965) were implemented in the spectral model to parameterize convection. The spectral model has performed quite well, overall, when compared with the LFM, especially in the Atlantic, Arctic and Pacific regions. The inadequate horizontal resolution has been identified as a weakness of the model. Since the fine detail in the analysis is removed by spectral truncation, local orographic effects are missing, vertical motion is underestimated and the moisture fields poorly represented, and the smallest synoptic scales are virtually

eliminated. Efforts to improve the precipitation forecasts led to the introduction of the Kuo (1965) scheme in 1985 (Simard and Girard, 1986). Preliminary indications suggest that the implementation of the Kuo scheme has improved the forecast of predicted summer precipitation.

The regional finite element model design has been described in Staniforth and Daley (1977, 1979). It has been running at CMC since late 1984, and its output available operationally since September 1985. The finite element model (Benoit, 1987) is a primitive equation, 15 level with sigma coordinate vertical resolution, 190 km resolution and parameterized physical processes. The physics considered in the model include: surface heat and moisture budgets; stability-dependent surface layer diffusion; land and ocean surface characteristics (surface roughness, albedo, surface temperature, deep soil temperature, ice cover, deep and surface soil moisture fraction and orography); condensation; free atmosphere convection; thermal and solar radiation; cloudiness; and horizontal diffusion. Forecasts of accumulated precipitation and instantaneous precipitation are available to the regional offices twice daily.

Verification of these models indicate that the QPF's have greater difficulty with convective precipitation forecasts than with forecasts of synoptically-organized precipitation (Toth, 1988).

The application of large-scale models to local and regional forecasts is also achieved by statistical means, specifically by the perfect prog approach and the imperfect prog approach. These approaches are characterized by the method in which the predictor values are selected and in the time differences in the predictor-predictand relationship. In the perfect prog approach, no time lag exists between the predictand and predictors. Therefore forecast predictor values must be used when the technique is applied to predict the predictand values. A large sample of observed historical data is used to develop the statistical prediction equation. The imperfect prog approach (or model output statistics) is

very similar to the perfect prog approach in that the predictor-predictand relationship is derived with little or no time lag. The difference is that the forecast predictor values, instead of the observed predictor values, are used in the dependent sample to derive the prediction equation.

5.2.2 The US National Weather Service QPFs

The Limited-area Fine-Mesh (LFM) model is the principal source of NWS numerical guidance over the United States. Grid size of the current version of the LFM model (LFM-II) is 127 km at 60 degrees N latitude. The North American continent comprises the land model domain. It is documented in Gerrity (1977) and more recently in Newell and Deaven (1981). The LFM provides various forecast outputs including precipitation, temperature, pressure, and humidity for various levels in the atmosphere for each grid point. Forecasts are available every 12 hours, and forecast lead times extend up to 48 hours with both 6-hour and 12-hour resolutions. This model accounts for both a large scale precipitation process and a subgrid convective precipitation process. Determination of the large-scale precipitation rate is based on whether the value of the relative humidity computed at each grid point is larger than an empirically reduced saturation value, determined by the solution of the hydrodynamic equations. Convective precipitation is related solely to the prediction of the existence of a conditionally unstable air mass with vapor content exceeding an empirical threshold value. Large-scale precipitation is computed internally in the LFM model every six minutes, while convective precipitation is computed every hour.

For cases of severe storm or hurricane development, the NMC movable fine mesh (MFM) model is used (National Weather Service, Meteorological Services Division, 1979). It has the characteristics that its computational grid moves with the storm during its development. Apart from small changes in the primitive equations and the fact that the grid is movable, the MFM model is the same as the LFM model. The MFM computational grid is 60 to 100 km on a side and

the time resolution of the forecasts is 6 hours, with a maximum lead time of 48 hours.

The National Meteorological Center (NMC) spectral model, SMG3C (Sela, 1980), employs spectral functions instead of the finite-difference representation for the forecast domain. The major physical effects modeled are orography, surface friction, subscale horizontal dissipation parameterized by diffusion, both large scale and convective precipitation, and evaporation and sensible heat effects from the ocean. The SMG3C has both a global and hemispheric version. Comparative studies have found this model to be comparable in accuracy to primitive equations grid-point models with 191-km grid size. Forecast lead times for precipitation products up to 48 hours are routinely available.

The Model Output Statistics (MOS) method documented in Glahn and Lowry (1972) and Lowry and Glahn (1976) and the regression techniques used in the very short-term forecasting of severe local storms and thunderstorms (National Weather Service, Meteorological Services Division, 1981) are two examples of statistical models used operationally in the U.S.

Charba and Klein (1980) examined the skill in precipitation forecasting at the National Weather Service. The skill and accuracy of both measurable and quantitative precipitation forecasts was 35-55% greater during the cool season than during the warm season. This seasonal difference in performance reflects the relative difficulty of forecasting predominantly stratiform precipitation of the winter season and convective precipitation of the summer season.

5.3 Current Hydrological QPF Activities

Hydrological QPF activities are primarily directed toward spring runoff forecasting and flood forecasting. Flood forecasting in Alberta is provided by the River Forecast Centre of Alberta Environment. Real-time precipitation data obtained from telemetered

raingauge sites are input into the Streamflow Synthesis and Reservoir Regulation model (SSARR) and predictions of time of occurrence, peak discharge and duration of floods are made. Flood forecasting in Saskatchewan is provided by the Saskatchewan Water Corporation, and is based on techniques similar to those used in Alberta.

Streamflow forecasting in Manitoba is primarily conducted by the Water Resources Branch (MWRB) of the Manitoba Department of Natural Resources (Warkentin, 1983). Manitoba Hydro is the other agency in the province which conducts operations affecting river flows. During a spring flood, reports and forecasts are issued daily. For operational forecasting (when spring runoff has commenced) daily temperature and precipitation data obtained from AES are required. When runoff on the tributaries is well advanced, the most important input data for flow forecasting becomes the river stages and flows. The time window of the forecast period varies from days to weeks depending on the basin size and on the nature and progression of the runoff event. MWRB uses a graphical/statistical antecedent precipitation index (API) model known as MANAPI to forecast runoff. Model performance is evaluated both qualitatively and quantitatively. Qualitative evaluation consists of visually comparing plots of recorded and simulated flow hydrographs. Quantitative evaluation of model performance is based on correlation coefficients and standard errors of estimate between recorded and simulated runoff volumes and peak flows.

Current U.S. procedures employed for identification of potential, or actual, flash flood conditions are largely based on whether rainfall amounts exceed, or are expected to exceed, specified flash-flood guidance criteria provided by the River Forecast Centers (RFC) to the Weather Service Forecast Offices or Weather Service Offices. Flash-flood guidance values typically apply to areas the size of counties or to zones consisting of several counties. In addition, approximately 700 Local Flood Warning Systems are located in individual communities where flash-flooding has historically caused major problems or where the potential for flooding is high.

The second level of the hydrologic forecasting system is the larger-scale system running at the RFCs. The forecast system architecture and its component procedures vary somewhat among the 13 RFCs, although several currently use, and most others plan to use in the future, the National Weather Service River Forecast System (NWSRFS). NWSRFS (Hudlow and Brazil, 1982) provides a standard software framework that is flexible enough to allow the incorporation of unique operational procedures that may be required by a particular RFC mission or by the presence of special hydrometeorological conditions. NWSRFS consists of data entry, preprocessing, and forecast components, along with numerous utilities and supporting programs. It contains continuous conceptual hydrologic models that, for example, keep track of soil moisture conditions (Peck, 1976). NWSRFS is designed to handle forecast lead times down to one hour and up to several days.

5.4 Mesoscale models

Many significant meteorological events (such as severe local storms, flash floods, and freezing precipitation events) are recognized as being associated with mesoscale features (Orlanski, 1975; Fujita, 1981). Pielke (1981) proposed a dynamical definition of the mesoscale as those atmospheric circulations which have horizontal scales large enough to be essentially in hydrostatic balance, yet small enough so that the wind field deviates substantially from gradient wind balance above the planetary boundary layer. The mesoscale can also be defined more qualitatively as having a temporal and horizontal spatial scale smaller than the conventional rawinsonde network, but significantly larger than the size of individual cumulus clouds. Understanding the evolution of these features, their relationship to the synoptic circulation in which they are embedded, and predicting the occurrence of these small-scale disturbances is not complete.

Numerical models have been capable of simulating individual mesoscale phenomena, such as severe thunderstorms (Klemp and

Wilhelmson, 1978; Cotton and Tripoli, 1978; Clark, 1979), mesoscale convective complexes (Maddox et al., 1981), squall lines (Chang et al., 1981) and fronts (Williams, 1974; Shapiro, 1975; Ross and Orlanski, 1978). These studies have provided much insight into the dynamics and energetics of these phenomena. Considerable efforts are currently underway to develop theoretical models to improve our understanding and prediction of mesoscale storm systems.

The development of mesoscale features through numerical forecasts of severe local storms for two of the SESAME-1979 cases were examined by Anthes et al., (1982). Their study showed that a 10-layer model (Anthes and Warner, 1978) with a 100 km horizontal resolution, simple physics, and initialized with essentially synoptic-scale data, was capable of generating and maintaining mesoscale phenomena in the 0-24 hr time period. Ross and Orlanski (1982) simulated the 48-hr evolution of an observed cold front using an open-boundary three-dimensional model. Both of these studies suggest that the numerical prediction of smaller-scale disturbances could be achieved by increasing the resolution of the model and by including proper parameterization schemes for various physical processes.

The details and complexity that need to be considered in such a model are shown by using the UKMO model as an example. A mesoscale numerical forecast model with very fine resolution has been developed in the United Kingdom (Golding, 1984). The UKMO uses a 15 km-mesh on a transverse mercator projection. The model is nested in the operational 75 km-mesh regional model, which itself is nested in a 150 km-mesh global model. It covers the British Isles, except for the Shetlands, and is able to resolve all of the main topographic features. There are 16 levels (from 10 m to 12010 m) in the model and the vertical coordinate used is height above ground. The model is a non-hydrostatic, compressible model, and its basic dynamical equations have been described in Carpenter (1979) and Tapp and White (1976). Prognostic variables include cloud water, turbulent energy, temperature, wind and humidity. A major part of the computation involves the parameterization of the boundary layer processes

(including radiation, turbulent transport in the atmosphere and conduction in the ground), the layer cloud processes, and convective cloud processes. In the layer cloud parameterization, when moist air is cooled to saturation in the model, condensate is stored as cloud water. Precipitation forms when enough cloud water has accumulated. The scheme used is based on Sundqvist (1978) and consists of local rain production, accretion, and evaporation in subsaturated layers. The convective precipitation parameterization is based on Fritsch and Chappell (1980), modified for maritime cumulonimbus. Initialization is obtained by interpolating data from both the regional model and the mesoscale model. The upper-air analysis of mass and wind fields carried out in the regional model is interpolated to the mesoscale grid, on which boundary layer and cloud data are added using surface observations.

The UK system has been introduced into a semi-operational phase. Extensive verifications are being undertaken to establish its ability to provide short-range forecast guidance. Preliminary evaluations suggest that the model has produced some encouraging results. Forecasts of rain were verified by accumulating the success rate of a categorized prediction (Rain or no rain). The accuracy of predictions of rain or no rain was assessed at 84%. Further work to improve the features of the system is continuing.

The predictability of mesoscale phenomena by means of an 11-level 64 km mesh primitive equation model used by the Japan Meteorological Agency has also shown fairly high prediction accuracy (Ninomiya, 1985). However, the development and behaviour of some severe mesoscale phenomena are not always accurately predicted by the model. The results of such an attempt for a very severe local rainstorm even showed that although the accumulated precipitation amount was far less than that observed, the precipitation pattern was well simulated, and the area of heavy rain predicted agreed well with that observed. The study concluded that improvements in the physical parameterization of the condensation process and increased resolution are required to overcome the problems.

A detailed investigation of the predictive capabilities of the NASA Mesoscale Atmospheric Simulation System Version 2.0 (MASS 2.0) was performed by verifying 30 model forecasts against 149 strong convective systems observed by radar and satellite (Koch, 1985). The approach used to evaluate the mesoscale predictive capabilities of the model was to utilize observed patterns of convection as "verification" of the unfiltered forecast fields. Specifically, the study related the loci of convective predictor fields derived from the model forecasts to the loci of the individual mesoscale convective systems (MCSs) observed by radar. Two convective predictor variables, each of which includes measures of lifting and air mass convective instability, were defined. The results showed that using these variables, the genesis of 48% of the observed MCSs could be accurately related within 250 km and +/-3 hr of their observed formation, with a false alarm rate of 13%. Convection "underforecasts" were related in 67% of the instances to systematic forecast errors at the synoptic scale (Koch et al., 1985). The MASS 2.0 results demonstrate that the mesoscale model forecasts yielded coherent fields useful for the diagnosis of mesoscale processes relevant to the initiation of strong convection. Examples of the model "forecasts" of intense convective storm clusters, a severe squall line triggered along a dryline, orographically induced hailstorms, and sea breeze thunderstorms showed that the model can be used to gain insight into mesoscale convective processes in situations where synoptic-scale forecast errors have minimal impact.

A study by the Prairie Provinces Water Board (1974), aimed at determining the meteorological requirements for streamflow forecasting over the Saskatchewan River Basin, identified occluded cyclones as the storm type responsible for most of the persistent (3-day) extreme rainfall events over the basin. The spatial and temporal scales of the occluded lows were found to be compatible with the characteristics of intense rainfall producing storms. The study concluded that terrain-induced vertical motion is an important factor contributing to the rainfall distribution associated with an individual storm occurring over the Western Plains. Over the Canadian Western Plains,

occluded lows are often accompanied by a persistent north-easterly low-level flow of moist air adding an orographic or upslope component to the synoptic-scale vertical velocity pattern. The appropriate combination of topography and low-level wind provides additional lift to the already ascending air thereby increasing precipitation intensity.

The mesoscale boundary layer model developed by Raddatz and Khandekar (1977) was used to simulate upslope enhanced extreme rainfall events over the Saskatchewan River and adjacent drainage basins (Raddatz and Khandekar, 1979). In the model, precipitation is assumed to develop in a mixed layer ~ 2km deep. The model generates precipitation values over a 47.6 km grid mesh of 1369 points, thus it can provide estimates of the spatial distribution of precipitation useful for hydrological analysis. A case study based on observed initial conditions showed that the model could reproduce mesoscale rainfall distributions associated with an individual storm. With appropriate input, this model is capable of providing rainfall distribution data for short-term streamflow forecasts over the Saskatchewan River and adjacent drainage basins.

As part of CASP, a meso-α scale version of the regional finite-element model was set up for the short-term (36h) forecasting of East Coast storms (Mailhot et al., 1989). Refinements to the operational RFE model included a domain with increased horizontal resolution (100 km), a modified physics package, improved surface and geophysical field analyses, and the refinement of initial moisture analyses using satellite imagery. Mesoscale forecasts of precipitation types, and rain/snow rates were quite realistic when compared with actual station reports. The enhancement of the initial moisture analysis using satellite imagery generally increased precipitation amounts in the early hours of the forecast, but had little effect on the precipitation field after the first 12 h.

5.5 Scientific and Technical Requirements

It will be necessary to improve the numerical models if they are to adequately simulate mesoscale phenomena interacting over a range of scales. Heidemen and Fritsch (1988) reported that much of the significant summertime precipitation was convective and produced by mesoscale weather systems over mesoscale regions. The smaller spatial scales and more rapid development and evolution of mesoscale convective weather systems appear to be the main reasons that large-scale atmospheric models fail to predict the areal coverage and intensity of significant summertime precipitation events accurately. The basic requirement is to increase grid resolution. Innovative grid nesting procedures, including adaptive grids may be required (Droegemeier, 1988). MCSs and MCCs may pose the greatest challenge, requiring resolution of about one kilometer but a domain of over one thousand kilometers. The extension of synoptic-scale models, with typical grid sizes of 400 km, to smaller grid sizes has not been straightforward. There are four main difficulties according to Anthes (1983);

1) numerical difficulties associated with lateral boundary conditions,

2) limitations in the density of initial data, particularly upper-air data, on the regional scale,

3) the increase in importance of and difficulty in modeling diabatic, topographic, and surface effects, and

4) the reduction in the inherent predictability of smaller scale atmospheric circulations.

The first two are solvable with existing computer technology and advanced observational systems. Considerable progress in developing improved models of physical effects has been made. Improvements in predictions of the smaller-scale, or meso-α scale could be obtained through a combination of more effective usage of existing data, incorporating recent research results in observational models, and implementation of an improved data network.

The representation of the initial state of the atmosphere is of critical importance to the quality of the forecast that can be expected from the model. An issue that will require research will be the assimilation of real data into the model. Recent advances in technology, such as, wind profiler observations, Doppler radar data, VAS soundings, satellite soundings, and automatic surface data are providing frequent descriptions of atmospheric conditions. It will be necessary to sample, validate and integrate the large volume of data to produce an analysis of current conditions as input to numerical models. Benoit and Roch (1987) have designed a method to incorporate satellite-derived rainfall data into the initialization procedure of a high-resolution model. Lipton and Vonder Haar (1987) showed that the mesoscale analysis of the water vapor field provided better horizontal and vertical resolution when a numerical model (CSU Regional Atmospheric Mesoscale Modeling System) was coupled with satellite sounder data.

Another important area where improvements are required is in the models' parameterization of various physical processes. More realistic parameterizations of the condensation process have been identified. A convective parameterization more sensitive to mesoscale forcing and the subsequent forcing by the convection itself is needed. The CASP mesoscale modelling experiment (Mailhot et al., 1989) concluded that improvements in the forecasts of East Coast winter storms can be achieved through the use of numerical models with higher resolution and advanced physics, and can lead to the added benefit of improved quantitative precipitation forecasts.

Substantial increases in our ability to forecast mesoscale weather events are likely when improved numerical forecasts become available to forecasters. It will be important that the selected research models be evaluated as real-time forecast support tools. The questions that need to be addressed include:

1) Can the model be run realistically in real-time?

2) Can the output be processed, screened and displayed in ways

that do not overwhelm the user?

3) Can the model help to detect and forecast important mesoscale features accurately?

The means of verifying and assessing numerical mesoscale forecasts have not been defined clearly. A combination of objective and subjective methods should likely be used.

Georgakados and Hudlow (1984) in their discussion of QPF techniques as applied to hydrologic forecasting, identify a scientific requirement for research in modeling through coupled approaches to real-time precipitation/streamflow forecasting. This involves precipitation and streamflow models that are compatible in mathematical structure and spatial and temporal scales. Similarly, Henz and Kelley (1988) suggest a scientific requirement to evaluate a coupled hydrological/meteorological mesoscale flood forecast model in Western Canada. One approach they offer would be to select a basin or sub-basin in Alberta or Saskatchewan within the coverage of an operational weather radar. This basin could be instrumented with automated rain gauge and stream gauge networks and their Excessive Convective Rainfall model could be run during the summer.

CHAPTER 6
SUMMARY, CONCLUSIONS AND RECOMMENDATIONS

Quantitative convective precipitation forecasting (QCPF) is the prediction of localized rainfall duration, amount and areal extent associated with convective weather systems. Currently, probabilistic forecasts of rain and snow with pre-determined qualifiers are issued by AES. QCPF products are not routinely prepared in the forecast offices. Their availability during periods of severe thunderstorm threats would improve estimates of local flood potential, thereby assisting municipal, provincial and federal disaster service agencies in their provision of appropriate warnings to citizens in affected areas.

A considerable research effort will be required to improve the forecasts of mesoscale convective precipitation events. As a first step in determining the requirements for research and further technique development, a study was initiated to review the needs for specific forecast parameters and the ability of our current knowledge of convective storms and existing forecast techniques to provide this information. This project was jointly sponsored by the Hydrometeorological Research Division of the Canadian Climate Centre, the Central Region of Atmospheric Environment Service, and the Resource Technologies Department of the Alberta Research Council.

6.1 Need for QCPF

The first objective of this study was to identify and prioritize the needs and requirements of water resource managers and other appropriate groups for quantitative convective precipitation forecasts.

A questionnaire was formulated in co-operation with the Hydrometeorological Research Division and the Atmospheric Environment Service, and sent out to a wide spectrum of water resource managers.

The survey results showed that a need for quantitative convective precipitation forecasting exists in a variety of sectors, including agriculture, forestry, construction, urban hydrology, transportation, and public safety. Accurate information regarding rainfall amounts and geographical area were identified as the two most important forecast products required.

6.2 Current status of QCPFs

The second objective was to review the current state of scientific knowledge, forecast techniques and technologies related to quantitative convective precipitation forecasting.

An extensive literature review, coupled with a questionnaire and discussions with scientists and engineers active in the field, was conducted to determine the current state of QCPF and identify the scientific and technical requirements to make QCPF a reality. Four approaches have been identified to provide short-term forecasts of mesoscale weather events. The first approach extrapolates detailed observed weather patterns, the nowcasting approach. The second approach uses Model Output Statistics and statistical methods. The third approach relies on pattern recognition techniques, or the subjective methods used by forecasters. The fourth approach predicts using a mesoscale numerical model, the dynamical approach.

Considerable effort has been expended on developing specialized nowcasting techniques for convective rainfall. These usually involve a remote sensing system (satellite and/or radar), special radar and satellite data processing algorithms, a fully automated meteorological work station, data displays, and sophisticated telecommunications systems. These techniques show considerable promise for producing usable forecasts out to one to three hours. In fact, as an example, a rainfall nowcasting technique for the Montreal region, developed by Austin and Bellon (1984), is presently used with considerable success. In weather offices, there is the potential to incorporate knowledge-based systems to perform many of the routine analyses of

data, thereby freeing the forecaster to concentrate on producing better forecasts faster. NEXRAD includes sophisticated data processing algorithms which provide the meteorologist with automated guidance products for nowcasting rainfall and flood potential.

Considerable efforts are also underway in developing theoretical models to improve our understanding and prediction of mesoscale storm systems. The smaller spatial scales and more rapid development and evolution of mesoscale convective weather systems appear to be the main reasons that large-scale atmospheric models fail to predict the areal coverage and intensity of these events accurately. The modelling community recognizes that future numerical models will require finer spatial resolution and additional model physics if objective forecasts of significant summer precipitation are to improve substantially. A number of mesoscale models have shown skill at predicting mesoscale events. The MASS 2.0 and the Penn State/NCAR (Zhang and Fritsch, 1988) models are encouraging. However, we should be cautious about how these successes can be transferred into improved operational forecasts. The model initial conditions are carefully attended to in these studies. In operational forecasts, the models may need to be initialized during a precipitation event. The UKMO model has produced encouraging results in an operational setting.

6.3 Recommendations

The third objective was to identify the best ways of meeting these requirements using existing forecast methodologies and technologies as they apply to the specification of the timing, location, and precipitation amounts and rates associated with convective storms.

The key to improving forecasts and warnings of mesoscale weather is a better understanding of the physical and dynamical processes governing these phenomena. The best way of meeting these requirements is outlined in the following recommendations.

Research into severe convective storms, and their relation with

larger scale processes, especially those generating localized heavy rainfall, is recommended. Specific regions must be identified for which QCPF's are judged essential. Initially, detailed studies of significant precipitation events in the selected areas should be conducted to help determine time windows and the forcing mechanisms necessary for convection.

The impact of these convective storms on local hydrology, particularly in an urban environment, should be investigated. The evaluation and understanding of hydrologic responses of watersheds are required. Better monitoring and forecasting of quantitative precipitation will lead to better streamflow forecasts. The development of computerized procedures to provide a quick means for estimating flood severity is recommended.

Studies in nowcasting heavy convective precipitation should be conducted. These efforts could adapt or develop methods to extrapolate convective rain fields from radar and satellite observations. One way to facilitate improvements in the nowcasting of convective precipitation would be to mount a field program in western Canada. The design and conduct of this program could be implemented using SESAME, CASP, and the Limestone Mountain Experiment (LIMEX) as models. Doppler radar, satellite, atmospheric sounding systems, and automated meteorological workstations would play important roles. Other options such as the participation in international projects, such as STORM, should be explored.

Studies in mesoscale numerical modelling should be conducted. Initial efforts could adapt existing regional models with mesoscale resolution, parameterized convection, and topography to reflect local conditions. From the hydrological point of view, it will be important that these studies include the development of coupled hydrological/meteorological models.

Collaboration between research and operational personnel should be encouraged in order to expedite the transfer of QCPF procedures and

techniques from the research to operational communities. Avenues to explore include staff exchanges and secondments, assistance to graduate students, and the establishment of a center, including a prototype forecast office, for the study of convective precipitation.

6.4 Scientific and Technical Questions

The last objective was to specify the scientific and technical questions which must be resolved in order to develop an adequate knowledge base and effective techniques for the provision of accurate and relevant convective precipitation forecasts.

A number of scientific and technical questions pertaining to nowcasting and numerical modelling were identified.

Before the storm has formed, the problem is to decide where it will form. Specific questions raised include: What determines the locations of initial convective development? What is the inherent predictability of convective systems? An understanding of the influence of spatial variability in land use, soil moisture, and terrain and their interactions with propagating synoptic disturbances is required. How important is soil moisture in influencing convective precipitation?

Once the storm has formed, an important scientific problem is to relate radar reflectivity or the behaviour of clouds (as viewed by satellite) to rain rate. What environmental factors and microphysical factors are important in determining convective precipitation rates and durations? Further studies to improve the Z-R relationship in radar rainfall estimates are required.

If the formation of convective storms is to be modelled, issues concerning grid resolution, convective parameterization, model initialization, verification, and ultimately, the integration of these factors into operational forecasting need to be addressed. Specifically:

What observational detail is required in initializing forecast models? Can a convective parameterization be developed which adequately represents the observed distribution of convective precipitation? What resolution of convective cloud simulation is required to produce a good correspondence with the observed precipitation?

The technical problems primarily revolve about the immensity of the data sets required to provide accurate and relevant convective precipitation forecasts. Systems, based upon computer workstation facilities, need to be capable of handling large volumes of data from radars, satellites, and numerical models for viewing. The forecast products of the mesoscale prediction system need to be processed and distributed in a timely and efficient manner. FRONTIERS has demonstrated that nowcasts are, by their very nature, highly perishable, and must be disseminated promptly if they are not to lose their value. There are a number of prototypes already in existence that show promise. The PROFS system in the United States was developed to help design and assess local short-term forecast systems, from observations to dissemination.

Mesoscale research activities are increasing in Canada. The Canadian Atlantic Storms Program (CASP) was designed to improve the understanding and prediction of severe East Coast winter storms. CASP also provided an opportunity to test and refine new techniques and instrumentation. The Canadian Meteorological And Oceanographic Society's mesoscale sub-committee is currently developing a scientific plan for mesoscale activities in the next decade. Water-related issues such as, heavy precipitating storms, and evaporation have been identified as the primary mesoscale issues related to summer convective storms on the prairies. We believe that this report has addressed those critical issues related to quantitative convective precipitation forecasting.

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APPENDIX A

WATER RESOURCE PLANNERS

Name	Affiliation	Location
Mr. E. Kerr	Hydrology/Technical Services Alberta Environment	Edmonton, Alta
Mr. R. Keith	Alta Recreation and Parks	Edmonton, Alta
Dr. J.M. Powell	Northern Forestry Centre	Edmonton, Alta
Mr. P. Dzikowski	Conservation and Development Alberta Agriculture	Edmonton, Alta
Mr. R. Deeprose	Technical Services Division Alberta Environment	Edmonton, Alta
Mr. B. Janz	Alberta Forest Service	Edmonton, Alta
Mr. G. Vincent	Operations Branch Alberta Transportation	Edmonton, Alta
Mr. F.T. Nesbitt	Alberta Public Safety Services	Edmonton, Alta
Mr. R. Neuman	Design and Construction Transportation Dept City of Edmonton	Edmonton, Alta
Mr. H. Gongos	Roadway Operations Transportation Dept City of Edmonton	Edmonton, Alta
Mr. J. Vos	Water and Sanitation Dept City of Edmonton	Edmonton, Alta
Mr. S. Poole	Rossdale Water Treatment Plant City of Edmonton	Edmonton, Alta
Mr. W. Kuhnke	Technical Services Division Flow Forecasting Branch Alberta Environment	Edmonton, Alta
Mr. R.B. Wilson	Disaster Services Agency City of Edmonton	Edmonton, Alta
Dr. T.W. Krauss	Intera Technologies Ltd.	Calgary, Alta
Mr.J. McAuley	Engineering Dept. Sewer Div. City of Calgary.	Calgary, Alta

Name	Affiliation	Location
Mr. J. Sealy	Engineering Dept. Sewer Div. City of Calgary.	Calgary, Alta
Mr. D.A. Jamieson	Waterworks Division City of Calgary	Calgary, Alta
Mr. W. Nemanishen	Alberta Regional Division Prairie Farm Rehabilitation Admin	Calgary, Alta
Mr. M.O. Spitzer	Water Resources Branch Environment Canada	Calgary, Alta
Mr. J. Chomistek	Alberta Special Crops Horticulture Research Centre	Brooks, Alta
Mr. J. Webber	Eastern Irrigation District	Brooks, Alta
Mr. R. Jones	Irrigation Division Alberta Agriculture	Brooks, Alta
Mr. D. McKenzie	Irrigation Division Alberta Agriculture	Brooks, Alta
Mr. R. Winter	Irrigation Division Alberta Agriculture	Brooks, Alta
Dr. N. Foroud	Agricultural Research Station	Lethbridge, Alta
Mr. R. Riewe	Irrigation Branch Agriculture Centre	Lethbridge, Alta
Mr. R. Hohm	Alberta Agriculture	Lethbridge, Alta
Mr. R.T. Heywood	Conservation and Development Agriculture Research Centre	Lethbridge, Alta
Dr. C.W. Lindwall	Soil Science Section Lethbridge Research Station Agriculture Canada	Lethbridge, Alta
Mr. C. Vos	Alberta Agriculture	Strathmore, Alta
Mr. W. Chapman	Alberta Agriculture	Barrhead, Alta
Mr. L. Healy	Alberta Agriculture	Vauxhall, Alta
Mr. W.F. Thiele	Saskpower	Regina, Sask
Mr. G.A. Sephton	Prairie Farm Rehabilitation Administration	Regina, Sask

Name	Affiliation	Location
Mr. G. Nieminen	Municipal Engineering Dept City of Regina	Regina, Sask
Mr. A. Eagle	Prairie Farm Rehabilitation Administration	Regina, Sask
Mr. A.B. Banga	Saskatchewan Water Corporation	Moose Jaw, Sask
Mr. D.W. Gibson	Waterworks, Waste and Disposal City of Winnipeg	Winnipeg, Man
Mr. A.D. Cormie	Manitoba Hydro	Winnipeg, Man
Mr. A.A. Warkentin	Water Resources Branch Manitoba Department of Natural Resources	Winnipeg, Man
Dr. M. Gow	Waste Management Branch Ministry of Environment	Surrey, B.C.
Dr. K.F. Heideman	NOAA/ERL/PROFS	Boulder, Colo
Dr. M. Kelsch	NOAA/ERL/PROFS	Boulder, Colo

APPENDIX B

USER QUESTIONNAIRE

Quantitative precipitation forecasts are presently available for rainfall produced by large weather disturbances. The present study examines the usage of these forecasts by government agencies, the private sector, and others and considers the need and desirability to expand precipitation forecasts to include quantitative estimates of rainfall for summer showers and thunderstorms. This questionnaire is intended to incorporate your professional views in this study. Please feel free to solicit comments and opinions of your colleagues as you deem appropriate.

Please continue your answers on additional sheets as necessary. We thank you for your assistance.

QUESTIONS

1. Do you currently use precipitation forecasts in the conduct of your business or profession? Yes ____ No ____

   If your answer is yes, please go to question 2.
   If your answer is no, elaborate if you wish and then go to question 8.

2. What precipitation forecast information do you currently use? (check appropriate items)

   a. ____ Probability of occurrence
   b. ____ Rainfall amounts
   c. ____ Rainfall intensity or rate of accumulation
   d. ____ Rainfall duration
   e. ____ Geographic areas affected
   f. ____ Beginning of rainfall (time)
   g. ____ End of rainfall (time)
   h. ____ Other (please specify below)

3. Where do you obtain these forecasts?
(check appropriate items)

a. ____ Radio
b. ____ Television
c. ____ Newspaper
d. ____ Directly from Atmospheric Environment Service (e.g., via telephone)
e. ____ Consultants
d. ____ Other (please specify below)

4. How do you apply these forecasts in your business or profession?

5. How do you rate the accuracy of these forecasts?
(check appropriate item)

Forecast Product	Accuracy Rating		
	Good	Fair	Poor
a. Probability of occurrence	___	___	___
b. Rainfall amounts	___	___	___
c. Rainfall intensity	___	___	___
d. Rainfall duration	___	___	___
e. Geographic areas affected	___	___	___
f. Beginning of rainfall (time)	___	___	___
g. End of rainfall (time)	___	___	___
h. Other (please specify)	___	___	___
	___	___	___

Comments:

6. What economic value do you estimate these forecasts have for the conduct of your business or profession?

Comments:

7. During what months of the year do you have the greatest requirement for precipitation forecasts?

Comments:

8. There are many potential types of Quantitative Convective Precipitation Forecasts (QCPFs). Please rate the importance of the following forecast products:

Forecast product	Importance		
	High	Medium	Low
a. Probability of occurrence	____	____	____
b. Rainfall amounts	____	____	____
c. Rainfall intensity	____	____	____
d. Geographical areas affected	____	____	____
e. Beginning of rainfall (time)	____	____	____
f. End of rainfall (time)	____	____	____
g. Other (please specify below)	____	____	____

9. How would you foresee using these forecast products in the conduct of your business or profession?

APPENDIX C

EXPERTS CONSULTED

Name	Affiliation	Location
Dr. K.A. Browning	Meteorological Office	Bracknell, UK
Dr. W.R. Cotton	Dept of Atmospheric Science Colorado State University	Fort Collins, CO
Dr. M. Beland	Numerical Weather Research Atmospheric Environment Service	Montreal, Que
Dr. R. Benoit	Numerical Weather Research Atmospheric Environment Service	Montreal, Que
Dr. Y. Delage	Numerical Weather Research Atmospheric Environment Service	Montreal, Que
Dr. A. Tremblay	Numerical Weather Research Atmospheric Environment Service	Montreal, Que
Dr. A. Bellon	McGill Radar Weather Observatory	St. Anne, Que de Bellevue
Mr. H.P. Biron	Centre Meteorologique du Quebec	St. Laurent, Que
Dr. R. Adler	Severe Storms Lab Laboratory for Atmospheres NASA/Goddard Space Flight Center	Greenbelt, MD
Dr. J.P. Gerrity	Short-range Modelling Branch National Meteorological Center	Washington, DC
Mr. J.F. Henz	Henz Kelley and Associates	Denver, CO
Mr. R. Kelley	Henz Kelley and Associates	Denver, CO
Dr. L.R. Johnson	Institute of Atmospheric Sciences South Dakota School of Mines and Technology	Rapid City, SD
Dr. J. Wilson	Flight Observing Facility NCAR	Boulder, CO
Dr. F.H. Carr	School of Meteorology University of Oklahoma	Norman, OK
Dr. R. Scofield	Satellite Applications Lab NOAA/NESDIS	Washington, DC

Name	Affiliation	Location
Dr. R.A. Pielke	Dept of Atmospheric Science Colorado State University	Fort Collins, CO
Dr. T.W. Schlatter	ERL/PROFS NOAA	Boulder, CO
Dr. K. Heideman	ERL/PROFS NOAA	Boulder, CO
Dr. R.L. Holle	NSSL NOAA	Boulder, CO
Dr. K.E. Wilk	NEXRAD	Norman, OK
Dr. J.B. Klemp	NCAR	Boulder, CO
Dr. H.D. Orville	Institute of Atmospheric Sciences South Dakota School of Mines and Technology	Rapid City, SD
Dr. C.A. Doswell	NSSL	Norman, OK
Dr. C.G. Griffith	ERL/WRP NOAA	Boulder, CO
Mr. L. Legal	Prairie Weather Center AES	Winnipeg, Man
Mr. G. Moody	Prairie Weather Center AES	Winnipeg, Man
Mr. G. Machnee	Prairie Weather Center AES	Winnipeg, Man
Mr. B. Lawson	Prairie Weather Center AES	Winnipeg, Man
Mr. D. Patrick	Prairie Weather Center AES	Winnipeg, Man
Mr. C.D. Henry	Prairie Weather Center AES	Winnipeg, Man
Mr. K. Fluto	Prairie Weather Center AES	Winnipeg, Man
Mr. G. Schaefer	Prairie Weather Center AES	Winnipeg, Man
Mr. D. Burnett	Western Region AES	Edmonton, AB

Name	Affiliation	Location
Mr. T. Medlicott	Western Region AES	Edmonton, AB
Dr. E. Ferguson	NSSL	Kansas City, MO
Dr. F. Mosher	NSSL	Kansas City, MO
Mr. J. Arns	NSSL	Kansas City, MO
Mr. D. Matthews	NSSL	Kansas City, MO
Dr. D. Sirmans	NSSL	Norman, OK
Dr. R. Rabin	NSSL	Norman, OK
Mr. T. O'Bannon	NEXRAD	Norman, OK
Mr. K. Crawford	Weather Service Forecast Office	Norman, OK
Dr. L. Lemon	UNISYS	Norman, OK
Dr. D. Burgess	NSSL	Norman, OK
Dr. B. Maddox	NSSL	Norman, OK
Mr. A. Mohler	NEXRAD	Norman, OK
Dr. K. Droegemeir	U of Oklahoma	Norman, OK
Dr. G. Lessens	U of Oklahoma	Norman, OK
Dr. T. Schlatter	PROFS/NOAA	Boulder, CO
Dr. C. Bullock	PROFS/NOAA	Boulder, CO
Dr. R. Lopez	NSSL	Boulder, CO
Mr. S. Balint	Weather Services Forecast Office Stapleton Intnl. Airport	Denver, CO
Mr. K. Stewart	Urban Drainage and Flood Control District	Denver, CO

APPENDIX D

EXPERT QUESTIONNAIRE

Please feel free to continue your answers on additional sheets as necessary. We thank you for your assistance.

1. What scientific questions do you believe should be addressed to produce useful operational QCPFs?

2. What technical problems should be addressed to produce useful operational QCPFs?

3. What other QPF techniques/products might be applied to current quantitative convective precipitation forecasts (QCPFs)? What difficulties might be expected in doing this?

4. Do you have any opinion as to what mesoscale and regional numerical models show promise for operational production of QCPFs? Yes____ or No____. If yes, please elaborate.

5. What emerging technologies show promise for future operational production of QCPFs?

6. What strategy would you recommend to make accurate and timely QCPFs an operational reality as soon as possible? Please identify milestones that must be achieved.

APPENDIX E

NEXRAD HYDROMETEOROLOGICAL ALGORITHMS

Several precipitation algorithms are being developed and tested as part of NEXRAD hydrometeorological software support (NEXRAD Project Office, 1988). These include the following:

a) **Precipitation Detection** for determining whether precipitation is occurring and initiating gage data collection.

b) **Rain Gage Data Acquisition** for compiling and maintaining gage data transmitted by off-site computer for use by **Precipitation Adjustment**.

c) **Precipitation Preprocessing** for developing "hybrid scans", correcting for beam blockages, removing reflectivity outliers and isolated bins, and checking for excessive contamination by ground clutter and anomalous propagation.

d) **Precipitation Rate** for converting reflectivity to rainfall rate, for range correction, and for additional quality control checks for contaminated data.

e) **Precipitation Accumulation** for scan-to-scan accumulation, running hourly accumulations, checking for missing periods, and for additional outlier checks.

f) **Precipitation Adjustment** for adjusting accumulations for radar bias by merging gage and radar observations every hour using a Kalman filter.

g) **PPS Products** for one hour, three hour, and storm total graphical accumulations and for one hour digital accumulations.

h) **Precipitation Projection** for projecting precipitation one hour into the future through determination of localized storm velocities and error variances.

i) **Flash Flood Potential Assessment** for assessing the probability that rainfall will exceed a threshold value as obtained form appropriate River Forecast Centers; assessment is based on both observed and projected rainfall.

j) **FFP Products** for graphical displays of projected precipitation accumulation and observed and projected critical rainfall probability; for projected digital precipitation accumulation; and for zonal maximum critical rainfall probability and flash flood guidance summary, both in alphanumeric format.